**Supporting Information for:**

# Soft, curved electrode systems capable of integration on the auricle as a persistent brain-computer interface

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**Supporting Note 1.**

Fabrication process of epidermal electrodes follows exploits modified versions of otherwise conventional microfabrication techniques, together with processes of transfer printing.

a) Preparing of a carrier wafer

1. Clean a silicon wafer with acetone, IPA, and DI water.
2. Dehydrate it on a hot plate at 110 °C for 3 min.
3. Expose UV onto the wafer to make the surface hydrophilic for 3 min.
4. Spincoat PMMA on the wafer at 2000 rpm for 30 seconds.
5. Cure it on a hot plate at 180 °C for 2 minutes 30 seconds.

b) Material deposition and photolithography

1. Spincoat polyimide at 4000 rpm for 1 min.
2. Pre-bake it on a hot plate at 150 °C for 5 min.
3. Hard bake it in a hot oven at 250 °C for 2 hours.
4. Deposit 5nm/200nm-thick chromium/gold (Cr/Au) using an electron beam evaporator
5. Spincoat photoresist (AZ 5214) at 3000 rpm for 30 seconds.
6. Cure it on a hot plate at 110 °C for 1min.
7. Align(Metal#1) and expose UV (fractal and FS interconnect patterns).
8. Develop it with a base developer (917MIF).
9. Etch Cr/Au using chromium and gold etchant
10. Remove photoresist using acetone.
11. Spincoat 2nd layer of polyimide at 4000 rpm for 1 min.
12. Pre-bake it on a hot plate at 150 °C for 5 min.

13. Hard bake it in a hot oven at 250 °C for 2 hours.
14. Spincoat photoresist (AZ 4620) at 900/1100/4000 rpm for 10/60/20 seconds.
15. Cure it on a hot plate at 75 °C for 30 min.

c-1) Patterning of interconnects. Interconnects (non-sensing area) will have Au layer covered by polyimide layer.

1. Align(PI#2) and expose UV (encapsulation patterns on the pre-patterns). Develop it with a 1:2 mixture of base developer (400k) and deionized (DI) water. Photoresist remains in the connector pattern to protect etching of polyimide layer.
2. Etch the patterned two layers of polyimides using reactive ion etcher (RIE, March) at 150 W, 170 mTorr, 20 sccm oxygen for 1500 seconds.
1. Remove photoresist using acetone.

c-2) Patterning of sensors and contact pads. Sensors and contact pads will have Au surface exposed. Therefore, upon aligning and developing, PR will be removed.

1. Align(PI#2) and expose UV (encapsulation patterns on the pre-patterns). Develop it with a 1:2 mixture of base developer (400k) and deionized (DI) water. Photoresist layer in the sensors and contact pads is developed completely in order to etch the polyimide layer to expose patterned Au surface of the sensors and contact pads.

2. Etch the patterned two layers of polyimides using reactive ion etcher (RIE, March) at 150 W, 170 mTorr, 20 sccm oxygen for 1500 seconds.

3. Remove photoresist using acetone.

d-1) Preparation of a thick elastomeric membrane

1. Prepare a petri dish to hold silicone material
2. Mix part B, add part A, and mix together thoroughly (Solaris, Smooth-On). Spincoat the mixture in petri dish at 300 rpm for 1 min, which offers ~500 µm-thick substrate. Cure it at room temperature.
3. Gently detach silicone from the petri dish.

d-2) Preparation of a thin elastomeric membrane on PVA (polyvinyl alcohol; Haining Sprutop Chemical Tech, China).

1. Tape PVA onto a glass.

2. Prepare 2:1 Ecoflex (part B is 2) and spincoat at 3000rpm for 120s.

3. Cure it in a oven at 75 °C for 1 hour.

e-1) Pick up and transfer printing of electronics onto a thick membrane

1. Deposit $SiO_2$ (50 nm) using an electron beam evaporator.

2. Expose UV onto the targeted silicone for 3 min.

3. Transfer the patterns on the silicone substrate.

4. Dissolve the tape by putting them in water for 1 hours.

5. Bonding flexible electrical cable.

e-2) Pick up and transfer printing of electronics onto a thin membrane/PVA

1. Deposit $SiO_2$ (50 nm) using an electron beam evaporator.

2. Expose UV onto the targeted silicone/PVA substrate for 3 min.

3. Transfer the patterns on the silicone/PVA substrate.

4. Dissolve the tape by gently applying water on the water soluble tape only, applying water onto silicone/PVA substrate will dissolve PVA.

5. Bonding flexible electrical cable.

**Supporting Note 2**

Fabrication process of tri-polar electrodes follows exploits modified versions of otherwise conventional microfabrication techniques, together with processes of transfer printing.

1. Tri-polar fabrication continues after following all the steps in Supporting Note 1b.
2. Align(PI#2) and expose UV (encapsulation patterns on the pre-patterns). Develop it with a 1:2 mixture of base developer (400k) and deionized (DI) water.
3. Etch the patterned one layer(via) of polyimides using reactive ion etcher (RIE, March) at 150 W, 170 mTorr, 20 sccm oxygen for 600 seconds.
4. Remove photoresist using acetone
5. Deposit 500nm-thick Au using electron beam evaporator.
6. Spincoat photoresist (AZ 5214) at 3000 rpm for 30 seconds.
7. Cure it on a hot plate at 110 °C for 1min.
8. Align(Metal via#3) and expose UV (fractal and FS interconnect patterns). Develop it with a base developer (917MIF).
9. Etch Au using gold etchant.
10. Remove photoresist using acetone.
11. Spincoat photoresist (AZ 4620) at 900/1100/4000 rpm for 10/60/20 seconds.
12. Cure it on a hot plate at 75 °C for 30 min.
13. Align(PI#4) and expose UV. Develop it with a 1:2 mixture of base developer (400k) and deionized (DI) water.
14. Etch the patterned one layer of polyimides using reactive ion etcher (RIE, March) at 150 W, 170 mTorr, 20 sccm oxygen for 600 seconds.
15. Remove photoresist using acetone.

**Supporting Figure Legends**

**Fig. S1.** Fractal patterns based on 'Peano' curves that include arc sections to avoid stress concentrations at the corners. There are 2$^{nd}$ order iteration of Peano curves to form 'half-and-half' and 'all vertical' shapes.

**Fig. S2.** Fabrication process of epidermal electrodes: A) preparing a carrier wafer.

**Fig. S3.** Fabrication process of epidermal electrodes: B) material deposition and photolithography

**Fig. S4.** Fabrication process of epidermal electrodes: C-1) patterning of interconnects, C-2) patterning of sensors and contact pads, D-1) preparation of a thick elastomeric membrane, and D-2) preparation of a thin elastomeric membrane on PVA.

**Fig. S5.** Fabrication process of epidermal electrodes: E-1) pick up and transfer printing of electronics onto a thick membrane, E-2) pick up and transfer printing of electronics onto a thin membrane/PVA.

**Fig. S6.** Comparison of EEG alpha rhythms (spectrograms). (A) Noisy signals caused by incomplete mounting of the device. (B) Clear signals from the device with intimate contact to the skin.

**Fig. S7.** Results of finite element method for analysis of the epidermal device (electrode and interconnects) under uniaxial tensile loads. Scale bars show the maximum principal strains for fractal (metal) and substrate (silicone elastomer), respectively.

**Fig. S8.** Image of motion of the knee joint with the skin-mounted stretchable bandage that demonstrates the maximum deformation of ~50 % in length.

**Fig. S9.** EEG alpha rhythms recorded by epidermal electrodes mounted on the auricle and mastoid: spectrogram on the left shows the amplitudes of alpha rhythms when eyes were closed and plot on the right presents raw EEG signals as a function of the frequency.

**Fig. S10.** Images of electrolyte gel on a conventional electrode that shows a ~50 % reduction in volume due to evaporative drying over 6 hours.

**Fig. S10.** (A – B) Schematic illustrations that present the experimental setup including a skin replica (elastomer), gel electrode, mounting tape, and a hot plate: top view (A) and cross-sectional view (B). (C) Images of electrolyte gel on a conventional electrode that shows a ~50 % reduction in volume due to evaporative drying over 6 hours.

**Fig. S11.** (A) Image of a LTE electrode (inset: magnified view of the contact pads). (B) Image of a mounted LTE electrode on mastoid. (C) Image of positioning of the connector to the electrode by using a tweezer.

**Fig. S12.** (A) Schematics of the design of a releasable connector. (B) Image of the fabricated connector on a silicone elastomer that is integrated with anisotropic conductive films.

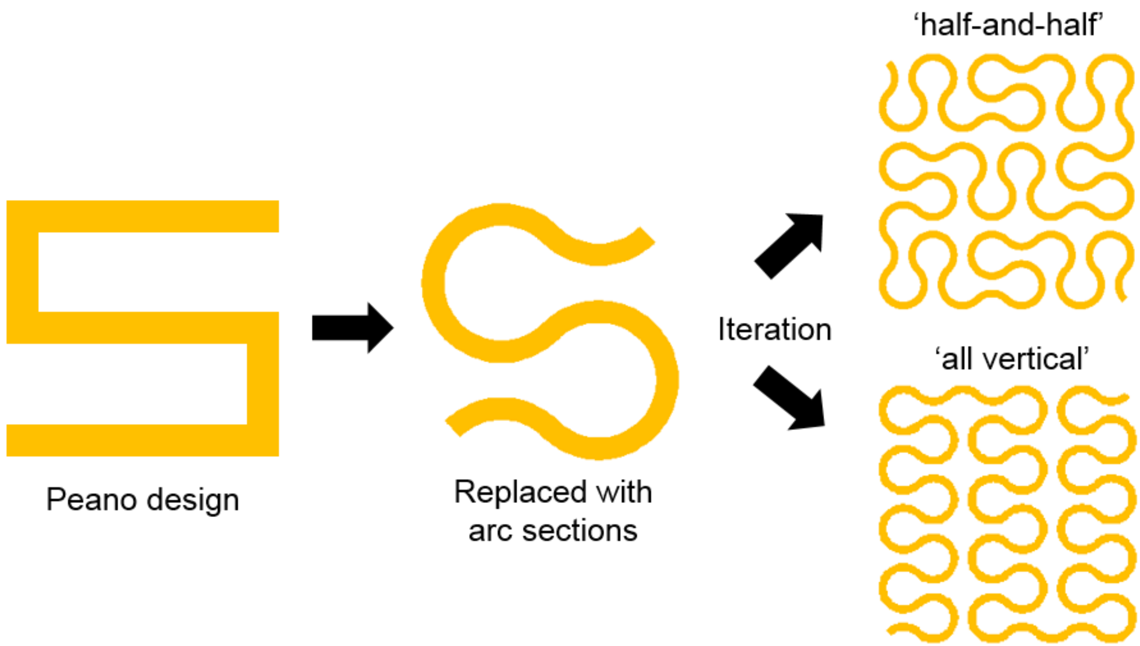
**Fig. S13.** Qualitative monitoring of the skin by a USB digital microscope (left) and the image of the skin (right).

**Fig. S14.** (A) Recording of P300 signals using a conventional electrode. (B) P300 data collected with the conventional electrode.

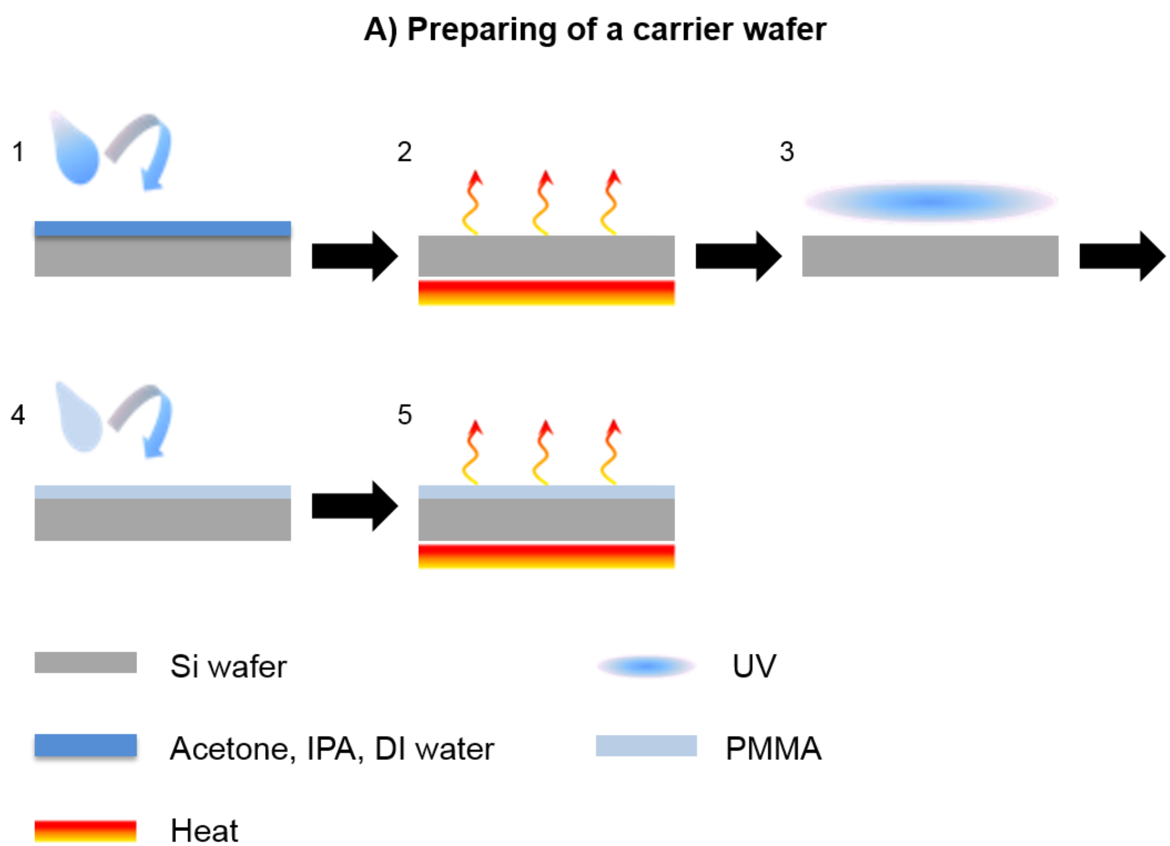
**Fig. S15.** Comparison of the size of electrodes between the conventional electrode and tripolar concentric ring electrode.

**Fig. S16.** Details of microfabrication steps for tripolar concentric ring electrodes.

**Fig. S17.** (A) Schematic diagrams of electrical circuits of the capacitive epidermal electrodes mounted on the skin. (B) Plot of pre-amplifier gain as a function of frequency.


‘half-and-half’
Iteration
‘all vertical’
Peano design
Replaced with
arc sections

# Figure S1


A) Preparing of a carrier wafer
1
2
3
4
5
Si wafer
UV
Acetone, IPA, DI water
PMMA
Heat

# Figure S2

## B) Material deposition and photolithography

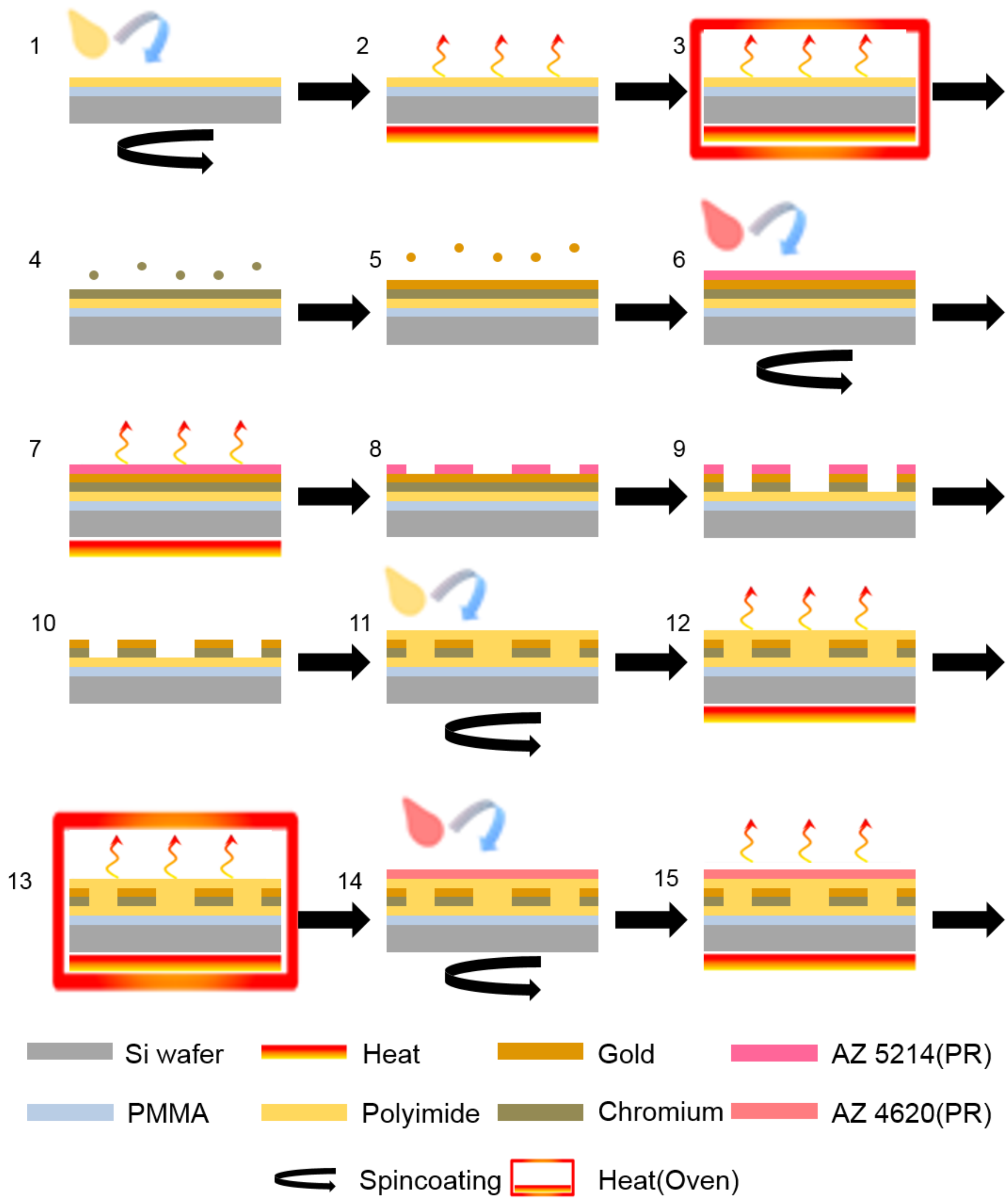



**Figure S3**

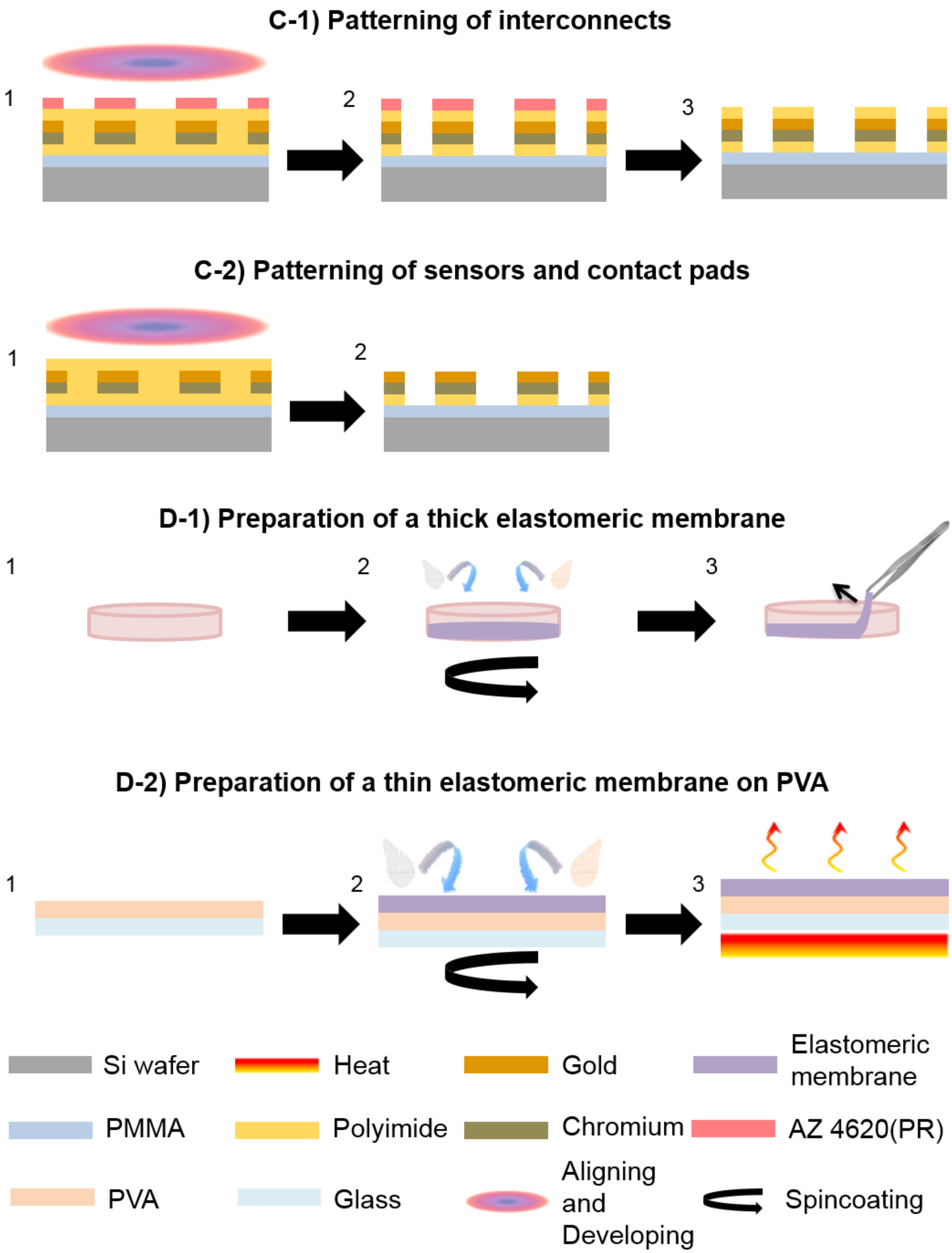
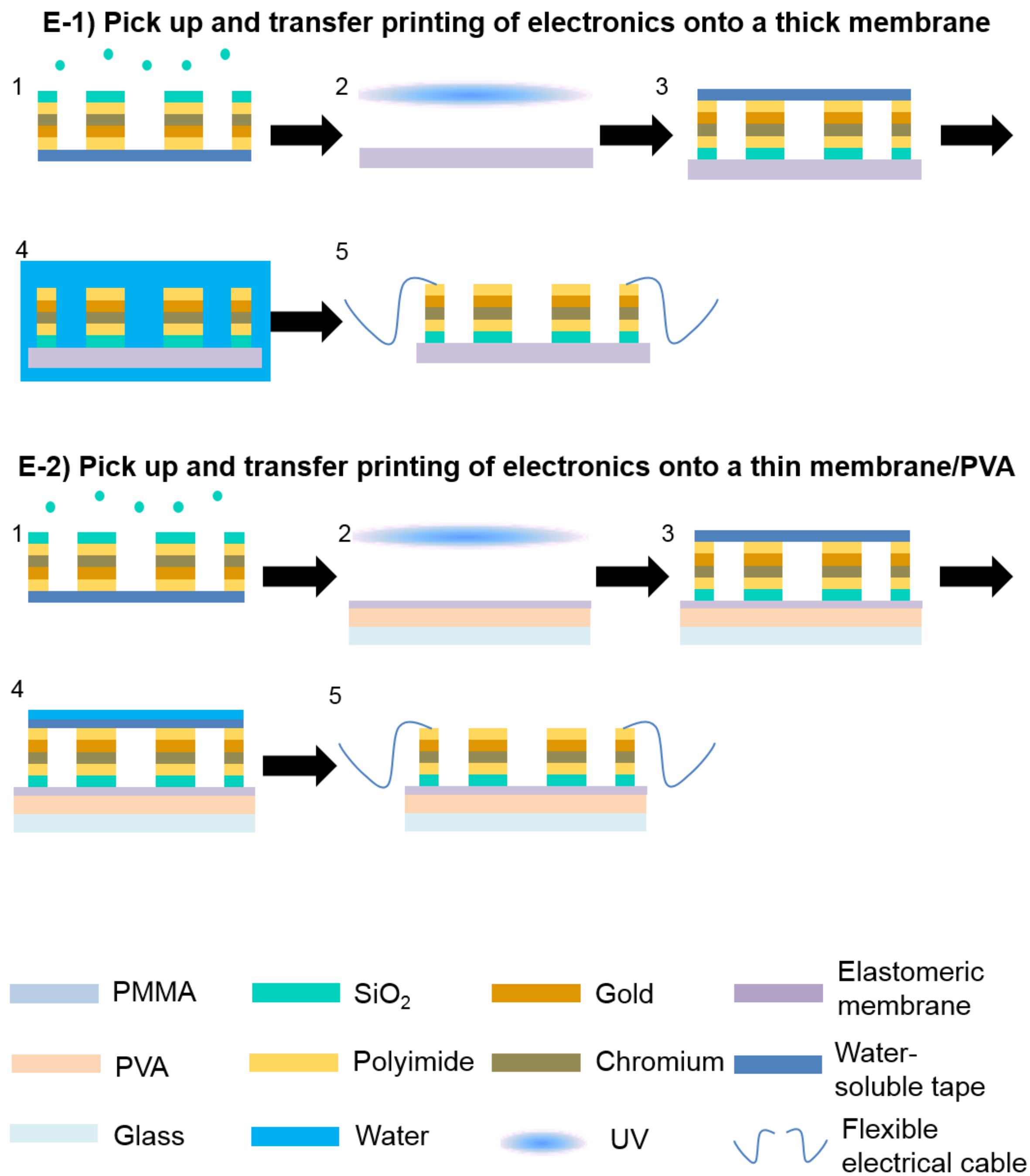
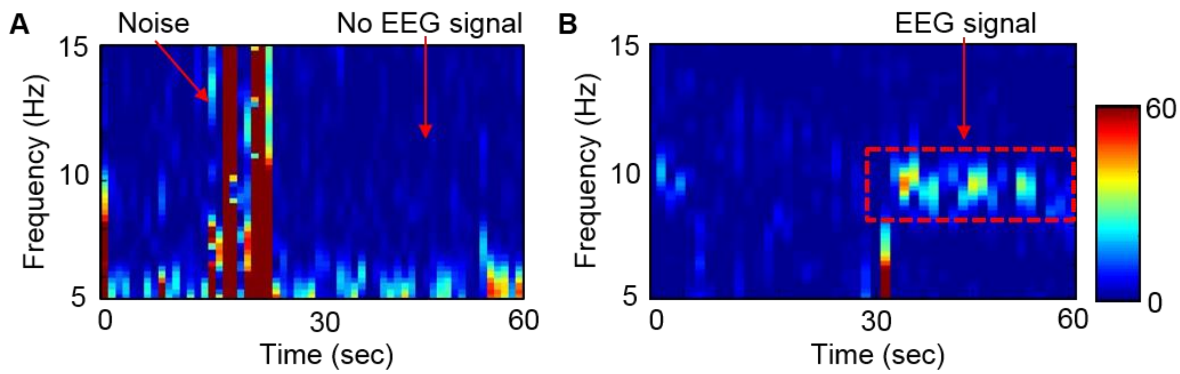

C-1) Patterning of interconnects
1
2
3
C-2) Patterning of sensors and contact pads
1
2
D-1) Preparation of a thick elastomeric membrane
1
2
3
D-2) Preparation of a thin elastomeric membrane on PVA
1
2
3
Si wafer
Heat
Gold
Elastomeric membrane
PMMA
Polyimide
Chromium
AZ 4620(PR)
PVA
Glass
Aligning and Developing
Spincoating

**Figure S4**

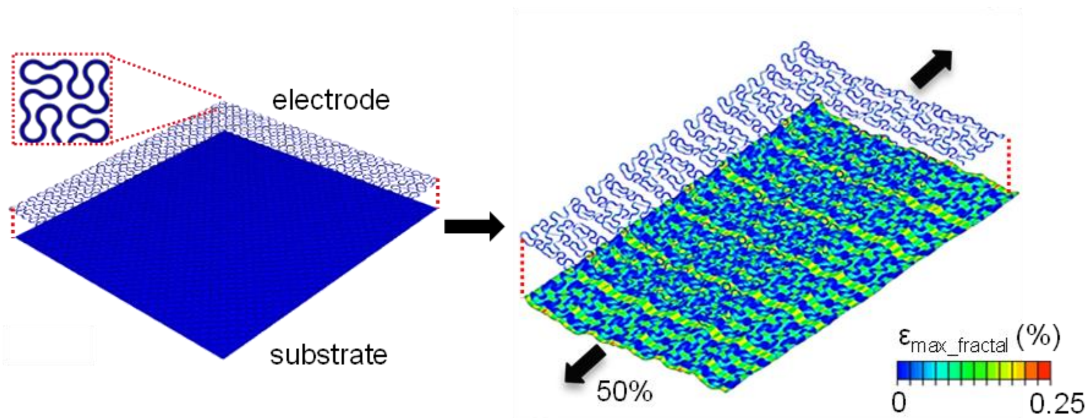


E-1) Pick up and transfer printing of electronics onto a thick membrane
1
2
3
4
5
E-2) Pick up and transfer printing of electronics onto a thin membrane/PVA
1
2
3
4
5
PMMA
$SiO_2$
Gold
Elastomeric membrane
PVA
Polyimide
Chromium
Water-soluble tape
Glass
Water
UV
Flexible electrical cable

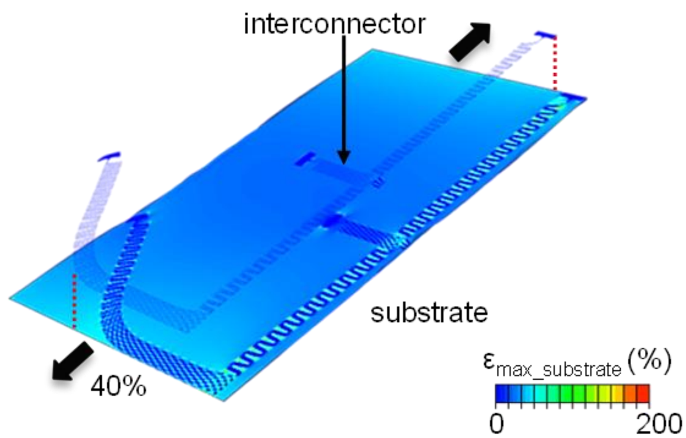

**Figure S5**


A
Noise
No EEG signal
15
10
5
Frequency (Hz)
0
30
60
Time (sec)
B
EEG signal
15
10
5
Frequency (Hz)
0
30
60
Time (sec)
60
0

# Figure S6

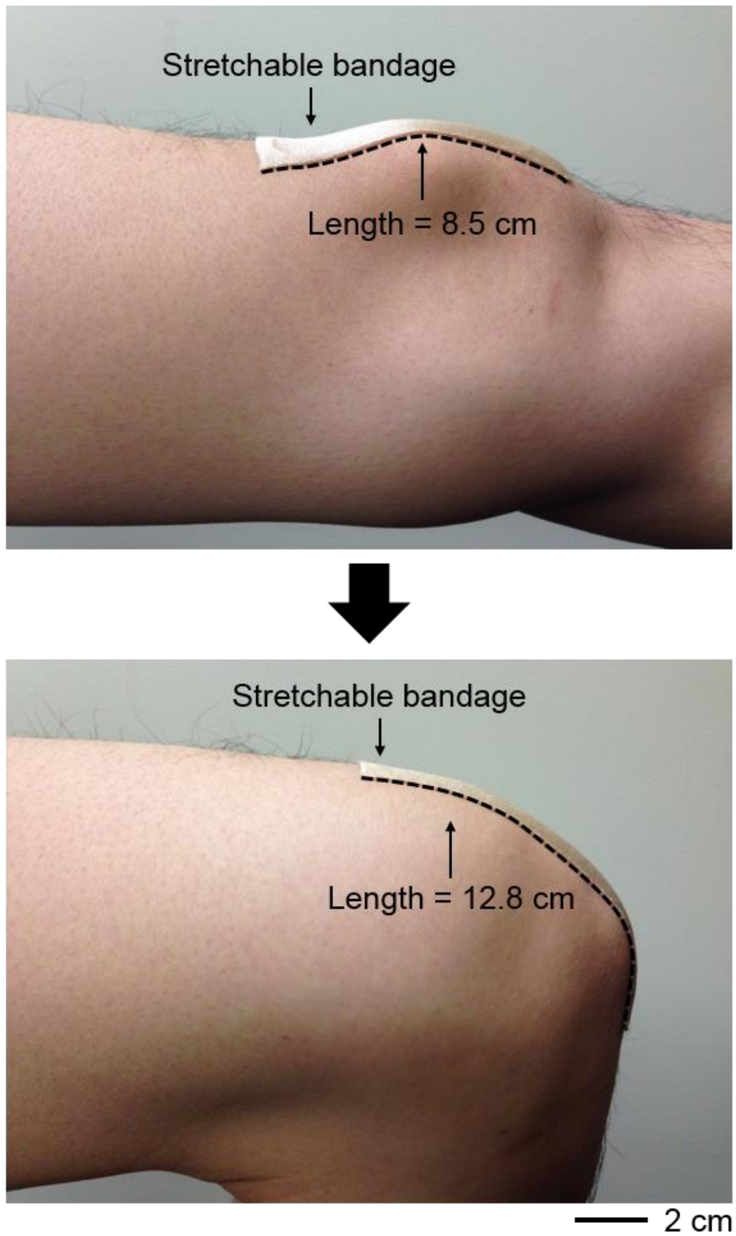


electrode
substrate
$\varepsilon_{max\_fractal}$ (%)
0
0.25
50%

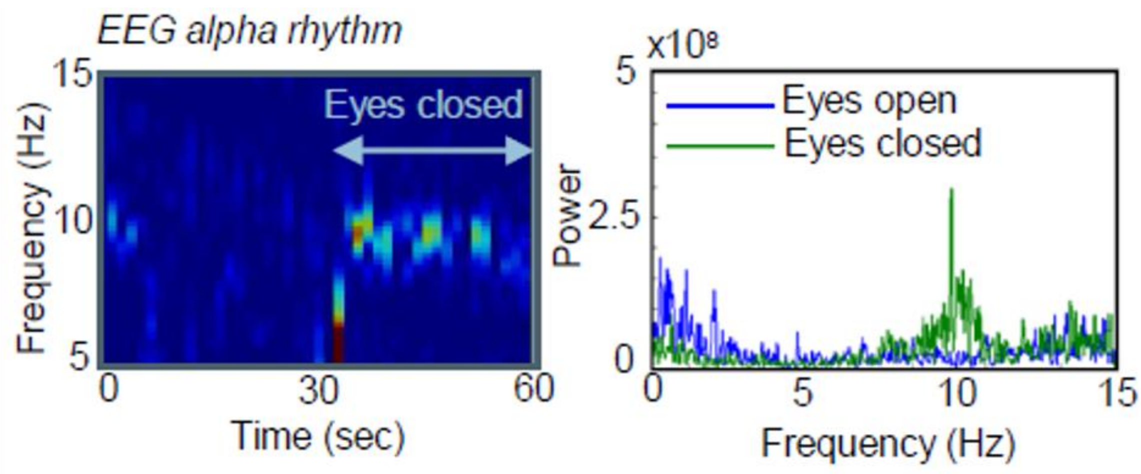



interconnector
substrate
$\varepsilon_{max\_substrate}$ (%)
0
200
40%


# Figure S7

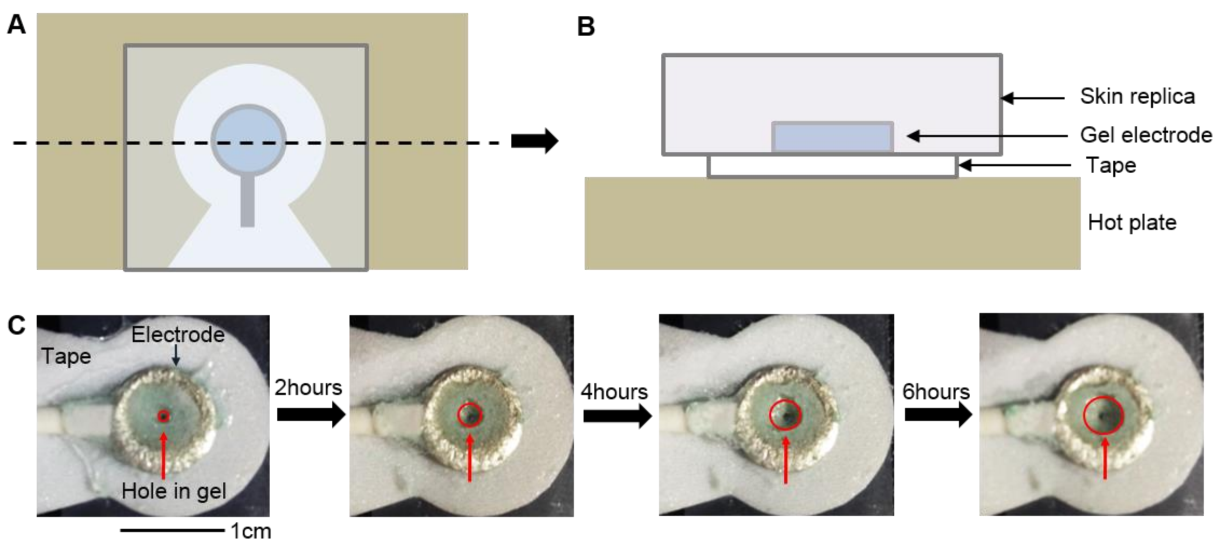

Stretchable bandage
Length = 8.5 cm
Stretchable bandage
Length = 12.8 cm
2 cm

# Figure S8

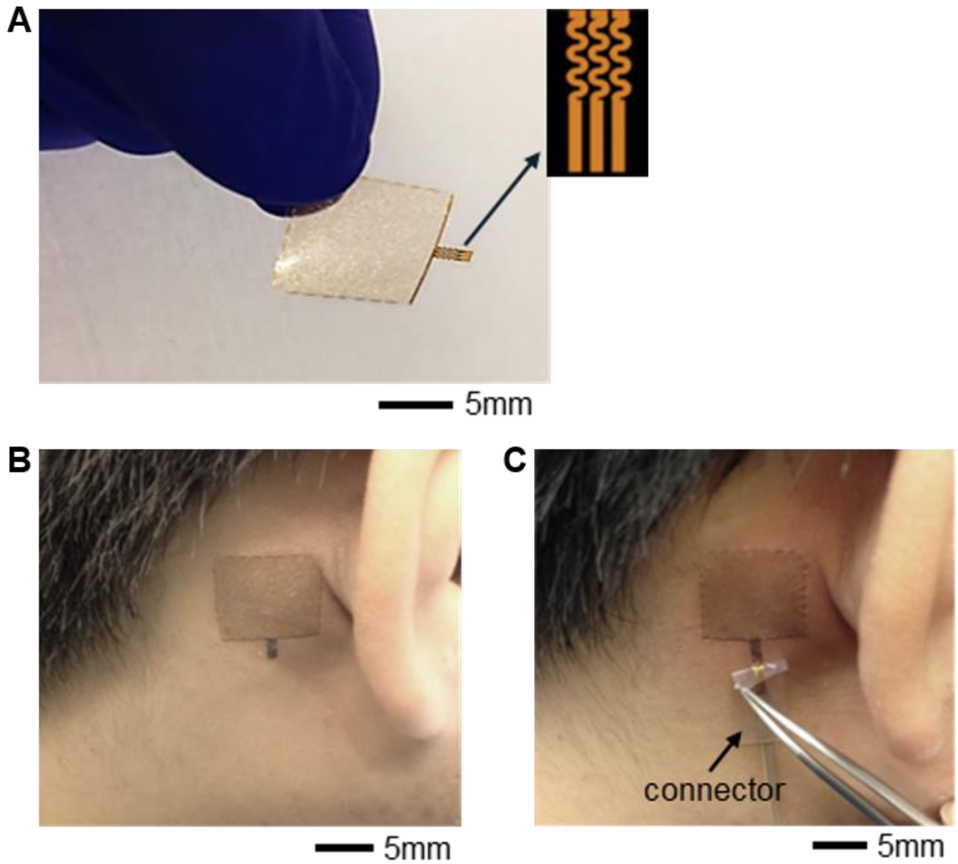


EEG alpha rhythm
Eyes closed
Frequency (Hz)
15
10
5
0
30
60
Time (sec)
x10⁸
5
2.5
0
Power
Eyes open
Eyes closed
0
5
10
15
Frequency (Hz)

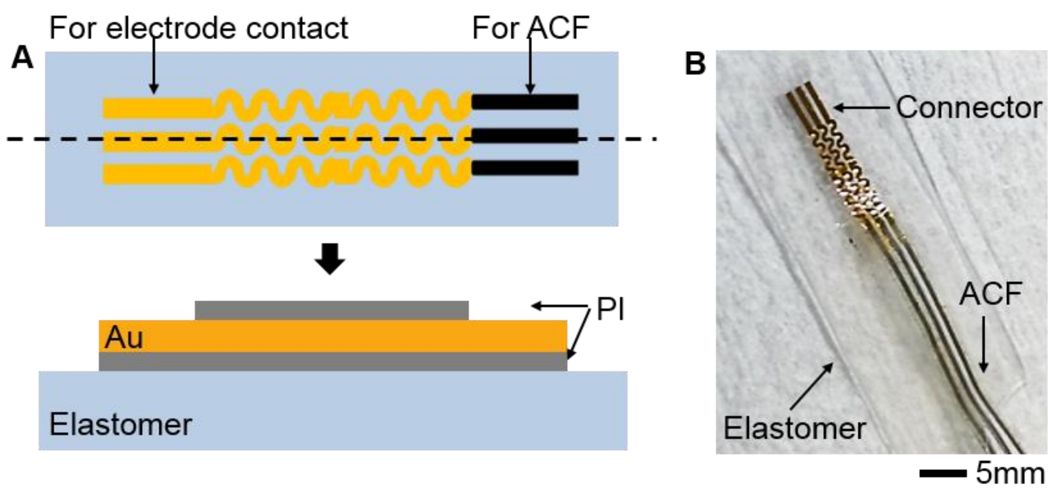

**Figure S9**


A
B
Skin replica
Gel electrode
Tape
Hot plate
C
Tape
Electrode
Hole in gel
1cm
2hours
4hours
6hours

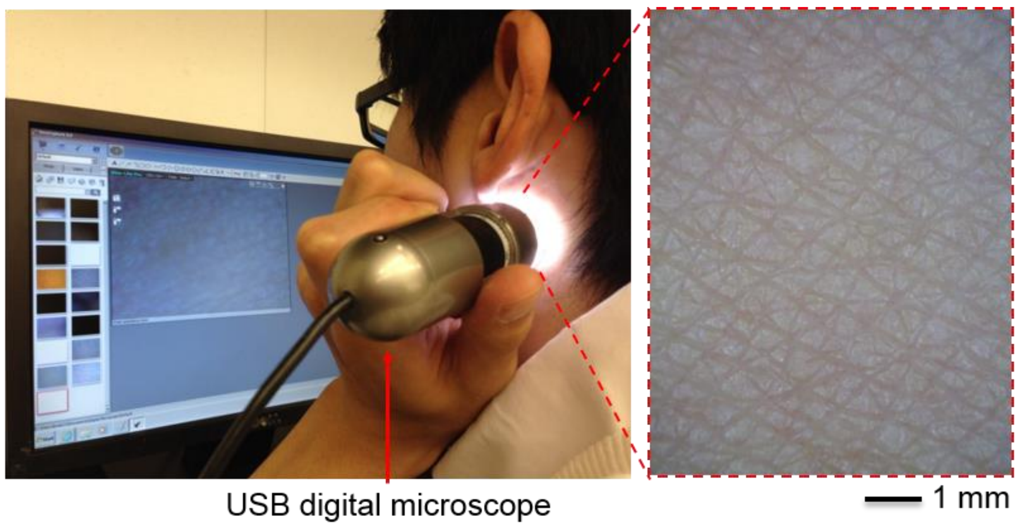
# Figure S10



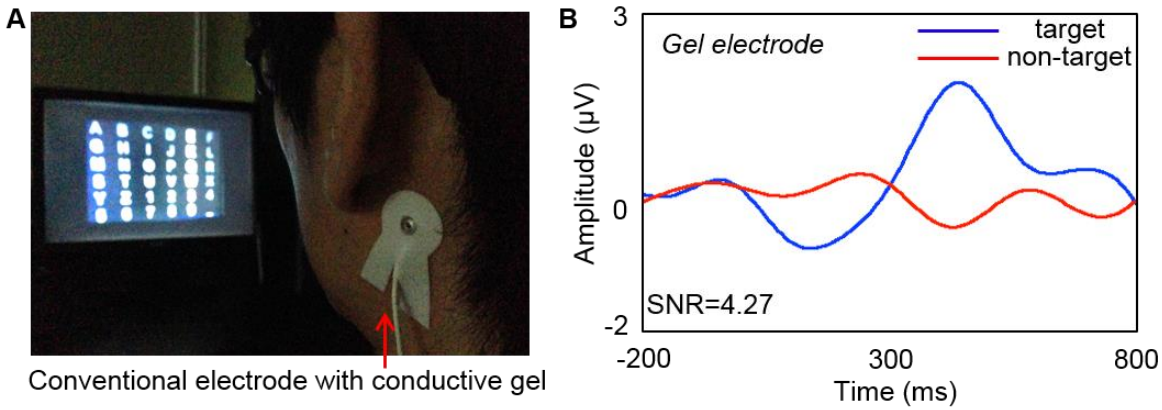

# Figure S11


For electrode contact
For ACF
A
Au
PI
Elastomer
B
Connector
ACF
Elastomer
5mm

# Figure S12




# Figure S13


A
Conventional electrode with conductive gel
B
Gel electrode
target
non-target
Amplitude (μV)
3
0
-2
SNR=4.27
-200
300
800
Time (ms)

# Figure S14

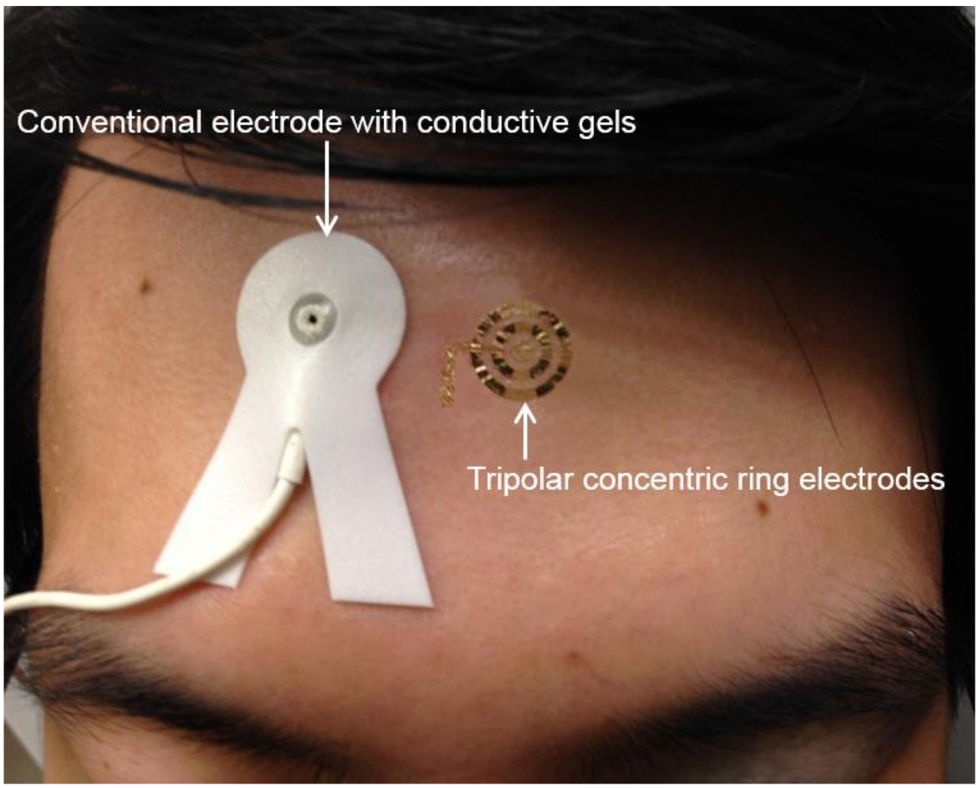

Conventional electrode with conductive gels
Tripolar concentric ring electrodes

**Figure S15**

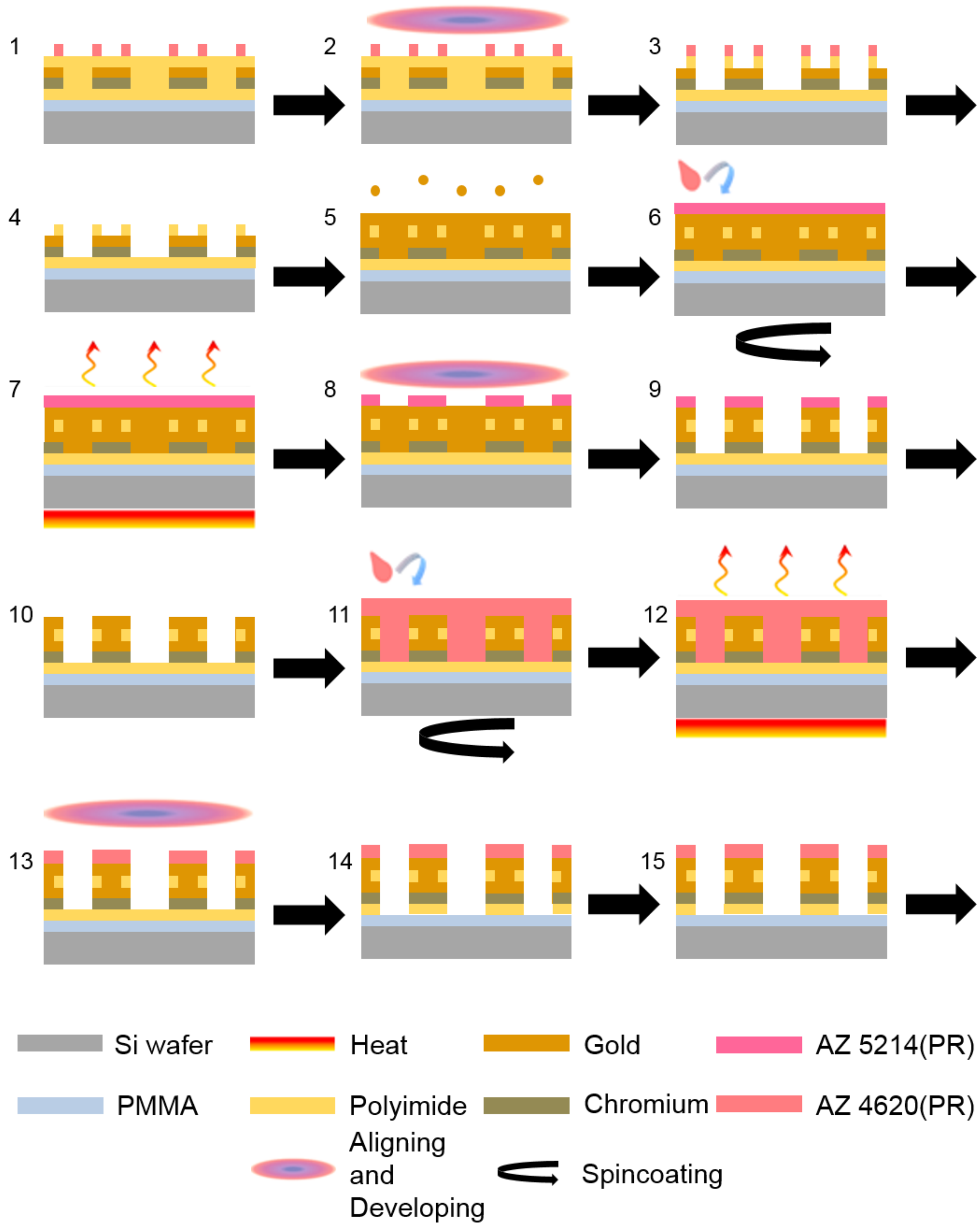
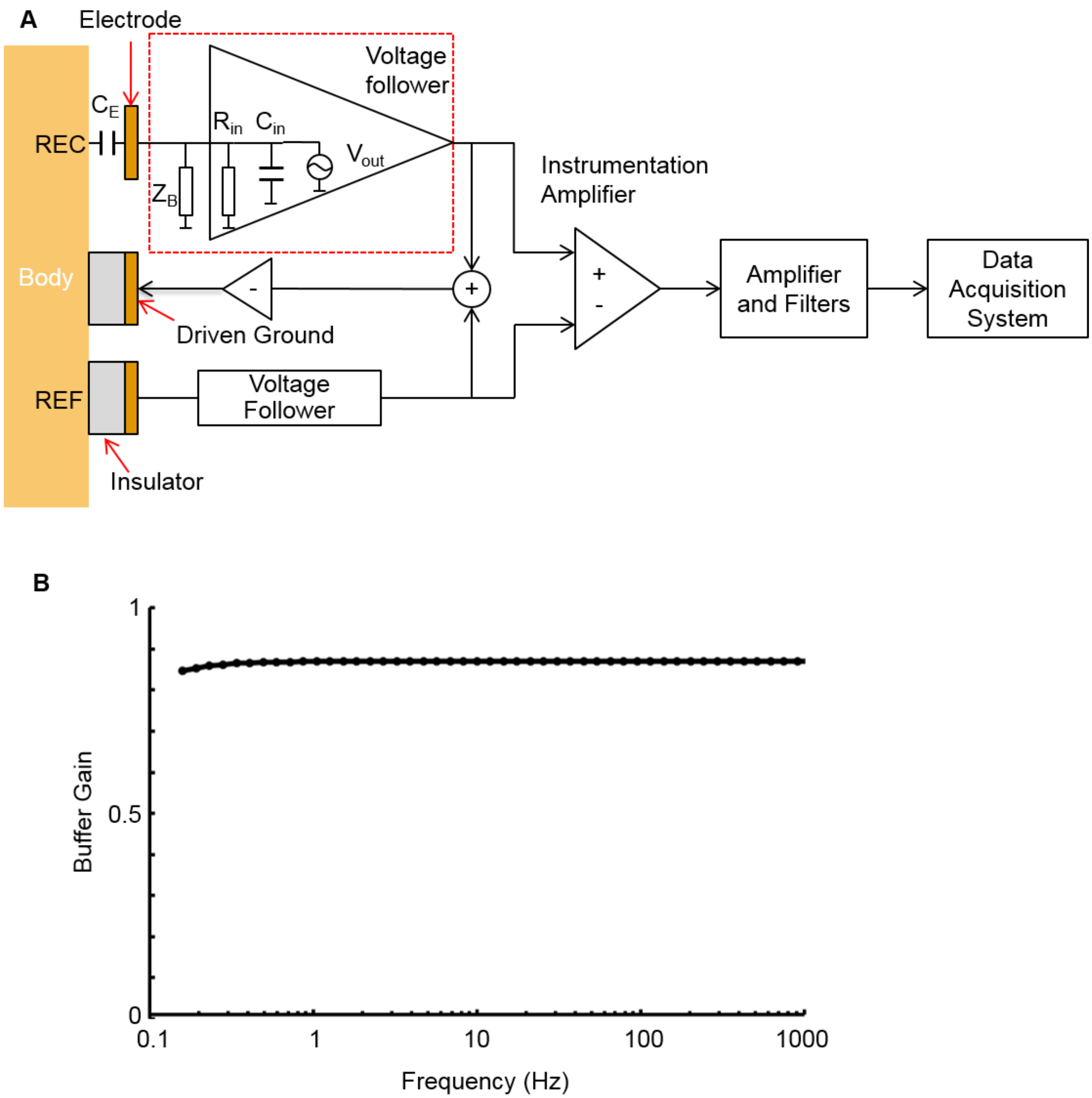

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Si wafer
Heat
Gold
AZ 5214(PR)
PMMA
Polyimide
Chromium
AZ 4620(PR)
Aligning and Developing
Spincoating

**Figure S16**


A
Electrode
Voltage follower
$C_E$
REC
$R_{in}$
$C_{in}$
$V_{out}$
$Z_B$
Instrumentation Amplifier
Body
+
-
Driven Ground
Amplifier and Filters
Data Acquisition System
REF
Voltage Follower
Insulator
B
Buffer Gain
1
0.5
0
0.1
1
10
100
1000
Frequency (Hz)

# Figure S17